Fuzzy Combustion Control for Reducing Both CO and NO<sub>x</sub> from Flue Gas of Refuse Incineration Furnace*

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NKK developed a new combustion controller that reduces both NO<sub>x</sub> and CO concentrations in the exhaust gas of municipal refuse incineration furnaces. We found that the manipulation of the cooling air flow rate is important because it affects the furnace temperature and the O<sub>2</sub>, NO<sub>x</sub> and CO concentrations in the exhaust gas. The new controller manipulates the cooling air flow rate. The controller monitors the furnace temperature and the O<sub>2</sub>, NO<sub>x</sub> and CO concentrations as process variables and then operates the cooling air flow rate as a manipulated variable. This multi-input/single-output controller was designed using a fuzzy control algorithm and tested on site at a municipal refuse furnace. The result of the on-site test was quite successful.

**Key Words:** Fuzzy Set Theory, Combustion, Environmental Engineering, Refuse Incineration Furnace, CO Reduction, NO<sub>x</sub> Reduction

1. Introduction

The reduction of harmful substances in the flue gas of municipal refuse incinerators requires technology to suppress their generation and technology to remove those generated. To avoid increasing the scale and complexity of flue gas treatment facilities, it is preferable to suppress the generation of harmful substances to the extent possible by controlling combustion.

Ordinary municipal refuse incinerators operate under an automatic combustion control (ACC) system and have achieved a lower level of harmful substances in the flue gas than the legal limits. Nevertheless, the pollution control requirements for municipal incinerators have become stricter year by year. For example, the Guideline for Controlling Dioxins Emissions from Municipal Solid Waste Incineration Plants was published in addition to existing regulations on NO<sub>x</sub>, HCl, and SO<sub>2</sub>. In response to these increasing social requirements, increasingly precise and fine combustion control will be needed to suppress the generation of harmful substances.

The simultaneous suppression of both CO-related Dioxins and NO<sub>x</sub> is considered to be difficult because the methods for suppressing CO and NO<sub>x</sub> conflict. However, we systematically observed a number of two-way flue-gas system furnaces and analyzed the resulting data. This study led to important findings for the simultaneous reduction of CO and NO<sub>x</sub>. This paper presents the findings, describes a fuzzy control system developed on the basis of the findings, and reports the results of applying the fuzzy control system to a commercial incinerator.
2. Two-Way Flue-Gas System Municipal Refuse Incineration Plant

Figure 1 shows the schematic diagram for a two-way flue-gas system, municipal refuse incineration plant. Since the quality of the collected municipal refuse is not uniform, a crane mixes the refuse before feeding it to the refuse hopper. The refuse fed into the incinerator travels slowly along fire grates by the reciprocating motion of the grates. While traveling along the grates, it is dried and spontaneously burned by preheated combustion air that is fed through the grates. The burnt refuse is then discharged as ash to outside of the incinerator.

The flue gas coming from the refuse layer is divided into two streams by the intermediate ceiling, which is a feature of two-way flue-gas system furnaces. The flue gas passes through the main flue gas passage, or through the bypass flue gas passage. Both flue gases then join back together in the gas mixing chamber where unburned gases are re-combusted.

Cooling air at ambient temperature is added to the combustion chamber and also to the flue gas passage section. After passing through the gas mixing chamber, the flue gas enters the boiler to recover the heat. It then enters the flue gas treatment system where harmful substances in the flue gas are removed before being discharged to the atmosphere. Steam from the boiler is used to run the turbine for generating power and to preheat the combustion air.

3. CO and NOx Generation Variables

3.1 Characteristics of CO generation

The CO concentration was measured at various points in the incinerator when the combustion state was stable to determine the variables contributing to CO generation. The CO concentration was several tens of ppm in the main flue, and several ten thousands of ppm in the bypass flue. Re-combustion in the gas mixing chamber reduced the CO concentration to as low as several ppm at the exit of the incinerator(2). (Fig. 2)

However, when the combustion becomes unstable, the unburned gas was not completely combusted, and the CO concentration at the exit of the incinerator showed a peak increase.

Figure 3 shows an example of the CO and O2 concentrations and the temperature in the gas mixing chamber through cyclic periods when peaks in the CO concentration occur. We systematically gathered and processed data from a number of commercial incinerators, and identified two cases of CO peak generation.

Case 1: The O2 concentration is low, and the temperature in the gas mixing chamber is high when the CO peak appears. The sudden increase probably comes from the rapid progress of refuse combustion, which uses up the O2, resulting in the increase of CO.

Case 2: The O2 concentration is high, and the temperature in the gas mixing chamber is low when the CO generation peak appears. This phenomenon probably comes from the low temperature in the gas mixing chamber, which prevents O2 from fully
Fig. 3  Relation among CO, O₂ and temperature

Fig. 4  Relation between NOₓ and cooling air

contributes to the re-combustion of CO, even when the amount of O₂ is sufficient, thus generating a significant amount of CO.

3.2 Characteristics of NOₓ generation

Although the mechanism of NOₓ generation is not completely understood, one tendency that has been observed is that an increase of the O₂ concentration in the incinerator produces an increase of the NOₓ concentration. We investigated the relation between the quantity of combustion air and that of NOₓ generated by linearly changing the feed rate of air into the incinerator. The result showed no distinct relation between them. However, when the cooling air flow rate was changed stepwise, the NOₓ concentration behaved as shown in Fig. 4. The results suggest a strong relation between the amount of cooling air and the NOₓ concentration.

3.3 Relation between CO, NOₓ, and temperature

Figure 5 shows a steady-state relation between the cooling air flow rate, the concentration of CO and NOₓ, and the temperature in the gas mixing chamber.

Fig. 5  Relation among CO, NOₓ and temperature

This relation was derived from data gathered from commercial incinerators in actual operation. Figure 6 summarizes the relation between these variables in a schematic form.

When the combustion state is in Zone I, the air flow rate into the incinerator is insufficient, so the amount of O₂ in the incinerator is extremely small. This results in incomplete combustion of CO, which increases the CO concentration. When the combustion state is in Zone III, an excess amount of cooling air enters the incinerator, lowering the temperature. This
decreases the combustion rate of unburned gas, which increases the CO concentration. In addition, the NO\textsubscript{2} concentration also increases with increases in the O\textsubscript{2} concentration. Consequently, the combustion state should be kept in Zone II, where both the CO and NO\textsubscript{2} concentrations are kept at low levels.

A peak increase in CO concentration can be seen in Fig. 3. When the combustion state is in Zone I, the insufficient amount of O\textsubscript{2} likely causes the CO concentration peak in Case 1. In Zone III, the low temperature in the gas mixing chamber probably causes the CO concentration peak in Case 2. Accordingly, a peak increase in CO concentration may be avoided by controlling the combustion state to stay within Zone II, where secondary combustion is the most vigorous.

4. Simultaneous Reduction of CO and NO\textsubscript{2} by Fuzzy Control System

4.1 Introduction of fuzzy control system

The sudden generation of CO is triggered by different causes that depend on the combustion state, as described in Chapter 3. Therefore, an accurate evaluation of the combustion state when the peak occurs and an adequate response is required to control the state. In this respect, fuzzy control should be suitable.

Features of a fuzzy control system are:

(1) Control rules are described using language.

(2) Optimal adjustment for each plant can be readily performed.

(3) Control targets can be flexibly added and changed.

Thus, the effectiveness of fuzzy control systems has been proven in various kinds of practical process control system applications. In particular, feature (1) is effective for controlling nonlinear processes, which permits stabilizing and maintaining the combustion state in Zone II of Fig. 6, even with sudden changes in the combustion state.

4.2 Functions of Fuzzy controller in the new ACC system

Conventional ACC systems use heat balance to stabilize combustion. The net calorific value of the incinerating refuse is determined by comparing the input, such as the amount of refuse charged, the flow rate and temperature of combustion air supplied to the incinerator, and the cooling air flow rate, with the output such as steam generated from boiler. In a conventional ACC system, the fluctuations in refuse combustion are stabilized by manipulating the combustion air flow rate and temperature and the grate travel speed to maintain a stable steam generation rate using the net calorific value. The cooling air flow rate is manipulated to cool the incinerator when the temperature gets too high.

In the new system as shown in Fig. 7, CO and NO\textsubscript{2} generation are reduced by using the fuzzy controller to manipulate the cooling air flow rate, and stabilization of refuse incineration is achieved on an average basis for long periods of operation by using a conventional ACC system for manipulating the combustion air flow rate, temperature, and the speed of the stokers.

4.3 Establishing fuzzy control rules

To simultaneously reduce the generation of CO and NO\textsubscript{2}, we established a set of control rules for adjusting the cooling air flow rate, based on the findings of CO and NO\textsubscript{2} generation characteristics described in Chapter 3. The first antecedent for the fuzzy control system consists of five input variables: \( x_1 \), the concentration of CO; \( x_2 \), the concentration of NO\textsubscript{2}; \( x_3 \), the concentration of O\textsubscript{2}; \( x_4 \), the gas mixing chamber temperature; and \( x_5 \), the cooling air flow rate. The consequent of the fuzzy control system is the setting of the cooling air flow rate. Part of the control rules and the membership functions are given in Table 1.

The symbols \( R_1 \) through \( R_5 \) designate individual control rules for changing the combustion state from Zone I in Fig. 6 (where a lack of oxygen is seen) to Zone II. The rule \( R_1 \) governs the state where the cooling air flow rate is low, resulting in incomplete secondary combustion. \( R_1 \) increases the cooling air flow rate to enhance secondary combustion and raise the temperature. The rule \( R_2 \) operates in the state where the oxygen concentration is low, which is likely to increase CO generation. \( R_2 \) increases the cooling
Table 1 Control rules of cooling air flow rate

<table>
<thead>
<tr>
<th>Rule No.</th>
<th>Input signals (Antecedents)</th>
<th>Output signal (Consequent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_1</td>
<td>CO, NOx, O_2, Temp.</td>
<td>Cooling air flow rate</td>
</tr>
<tr>
<td>R_2</td>
<td>Low, Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>R_3</td>
<td>High</td>
<td>Negative, Positive</td>
</tr>
<tr>
<td>R_4</td>
<td>Low, Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>R_5</td>
<td>High, Medium</td>
<td>Negative</td>
</tr>
</tbody>
</table>

Membership function

\[
\mu_i(x_i) = \begin{cases} 1 & \text{Low} \\ \text{High} & \end{cases} 
\]

CO, NOx, O_2, Temp.

\[
\mu_i(x_i) = \begin{cases} 1 & \text{Neg} \\ \text{Medium} & \text{Pos} \\ \text{High} & \end{cases} 
\]

Cooling air flow rate

- CO: CO concentration in exhaust gas
- NOx: NOx concentration in exhaust gas
- O_2: O_2 concentration in exhaust gas
- Temp.: Gas mixing temperature

cooling air flow rate should be decreased to reduce the temperature. For R_5, since NO_x generation is proportional to the cooling air flow rate, the cooling air flow rate is decreased to reduce NO_x generation.

By applying these rules, the combustion state is kept within Zone II, where the secondary combustion of flue gas is maximized. This reduces the CO concentration peaks as well as the average CO concentration level. Furthermore, NO_x generation is also reduced because unnecessary cooling air does not enter the incinerator.

In Fig. 6, the range of Zone II relative to the cooling air flow rate varies to some extent depending on changes in the refuse quality and incineration quantity. However, dealing with ambiguity is a feature of the fuzzy control system, and the system accommodates the fluctuations of these variables.

For making practical estimates, a simplified estimation method is used to derive the value of \( u^* \), and the set value of the cooling air flow rate \( u_s \) is determined by a velocity form algorithm. The simplified estimation method uses \( u_0 \) through \( u_6 \) as compatibility degrees for R_1 through R_5 in the antecedent given in Table 1. A singular expression is used for the consequent \( y_i \). This method was adopted because it eliminates the need to compute the center of gravity and because it allows high computation speeds.

\[
\begin{align*}
\omega_0 &= \mu_A(x_0) \times \mu_B(x_0) \\
\omega_1 &= \mu_C(x_1) \\
\omega_2 &= \mu_D(x_2) \\
\omega_3 &= \mu_E(x_3) \times \mu_F(x_3) \\
\omega_4 &= \mu_G(x_4) \\
\omega_5 &= \mu_H(x_5) \\
\omega_s &= \mu_i(x_i) \\
\omega_s &= \frac{\sum_{i=1}^{n} \omega_i}{n} \\
\end{align*}
\]

5. In-situ Test on Commercial Incinerator

5.1 Test result

The fuzzy control system was applied to a 150 ton per day incineration plant in normal service to verify the effect of the fuzzy controller for CO and NO_x reduction. Figure 8 shows the result of operation when manipulated only by a conventional ACC system. Figure 9 shows the result of operation when manipulated using both the ACC system and fuzzy control system to simultaneously reduce CO and NO_x. The concentrations of CO and NO_x shown in Figs. 8 and 9 are instantaneous values converted to 12% O_2 conditions. The figures show that the fuzzy control system suppresses the concentration of CO and NO_x to low levels. The NO_x concentration was reduced by an average of about 30 ppm. The average CO concentration was reduced, and no peaks were observed, as
On the other hand, the intermediate ceiling inside of the incinerator facilitates complete combustion of the unburned gas. The intermediate ceiling separates the flue gas into the main and bypass flue streams, so that the mixture of the flue gases is vigorous when they recombine in the gas mixing chamber. This can result in the complete combustion of the unburned gas. Thus, the new control system was developed by taking advantage of the structural features of the two-way flue-gas combustion system.

6. Conclusion

We developed a fuzzy control system to simultaneously reduce CO and NO\textsubscript{x} in stoker type municipal refuse incinerators. Practical application of the new ACC system demonstrated far superior control over that using only a conventional ACC system. The new control system can also be used for other types of conventional stoker inciners providing they have a unit to manipulate the cooling air flow rate and a secondary combustion chamber.

The fuzzy control system will reduce the operating cost of catalytic NO\textsubscript{x} reduction units that denitrify flue gas containing NO\textsubscript{x} by the injection of ammonia because the fuzzy control system suppresses NO\textsubscript{x} generation from the incinerator before being sent to the catalytic NO\textsubscript{x} reduction unit.

We are confident that this system with the fuzzy controller can fully meet the increasingly strict requirements for the reduction of harmful substances in flue gases.

References

